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Sustainable supply chain design in the food system with dietary considerations: A multi-objective analysis

S. U. K. Rohmer*, J. C. Gerdessen, G. D. H. Claassen

Operations Research and Logistics, Wageningen University, Hollandseweg 1, Wageningen 6706 KN, Netherlands

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ABSTRACT

Food is a vital component of everyday life, however current consumption and production patterns pose a threat to the environment and the food security of future generations. Thus, with environmental burdens becoming more apparent and rising societal awareness, it is time to reconsider dietary choices and the food system behind it. This paper presents a novel application of a network design problem, addressing sustainability issues in the context of the global food system. Taking into account several echelons and interlinkages between different food supply chains, the paper broadens the scope of the considered network and incorporates sourcing, processing and transportation decisions within a common framework. While minimising different environmental and economic objectives, the model aims to maintain a sufficient dietary intake level. Consumption decisions are incorporated in the model through different types of consumer demands. The problem is formulated based on linear programming and further analysis is carried out by applying the ϵ-constraint method and compromise programming. Investigating alternative production and consumption scenarios as well as trade-offs between the conflicting objectives, the study is illustrated based on a nutritional case study and underpinned by real-life LCA data. The findings of this research are manifold, highlighting the importance of considering consumption and production decisions in an integrated and global setting. Moreover, the choice of sustainability indicator plays a crucial role given the often conflicting nature of different sustainability aspects.

1. Introduction

Food does not only contribute significantly to our health and well-being but also plays a crucial role in global and local economic markets. However, with food systems being highly resource dependent, our diet also has implications for the environment we live in, both directly through the amount and combination of plant and animal products we consume and indirectly through the production of these products (Alder et al., 2012). On a global scale, food systems account for about 24% of the greenhouse gas emissions, 33% of the soil degradation as well as 60% of the terrestrial biodiversity loss (UNEP, 2016), while on a European level the food sector, and agriculture in particular, continues to be one of the most water and energy demanding sectors (Maguire, Belchior, Hoogeveen, Westhoek, & Manshoven, 2017). Meat and dairy products are among the products with the highest contribution to these environmental burdens (Notarnicola, Hayashi, Curran, & Huisingh, 2012; Steinfeld et al., 2006). A growing population combined with current unsustainable and wasteful food consumption and production patterns, marked by overconsumption and excessive consumption of meat and dairy products, aggravate these environmental threats and put further pressure on our environment in the form of global warming, resource depletion and the extinction of species (UNEP, 2016). Sustainable development, addressing economic, environmental and social issues, thus receives growing attention in the context of the food system.

The food system, however, with its transnational nature, is a highly complex and dynamic network involving multiple agents, a wide product variety and a large number of processes, ranging from production or manufacturing processes to logistic and retail activities (Trienekens, Wognum, Beulens, & van der Vorst, 2012). Furthermore, globalisation and differences in the affected social and ecological systems, such as climatic and geographical conditions or the development status of a country, affect the transparency and complicate sustainable decision making in the food system. A tomato grown locally in a greenhouse in the Netherlands, for example, will have a different environmental footprint than a tomato grown in Italy or Spain, as the activities and processes involved, such as transportation or energy input during production, will have different contributions to the overall environmental impact.

* Corresponding author.
E-mail addresses: sonja.rohmer@wur.nl, sukrohmer@outlook.com (S.U.K. Rohmer), joke.vanlemmen@wur.nl (J.C. Gerdessen), frits.claassen@wur.nl (G.D.H. Claassen).

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From a social perspective, health aspects and nutrition play the most prominent role in the food system with the UN defining food security and improved nutrition as one of its sustainable development goals (UN, 2015). There are many other aspects that could be considered in the context of the food system, such as equality between and within countries, working conditions or fair trade, however, these social impacts are often hard to quantify, measure and aggregate on a global scale. This research will thus focus on the nutrition and health aspect.

Economically, costs remain the key factor in the decision making process as profit margins for food products are often low, competition is high and the affordability of food in general is a key issue in today's society. It is therefore necessary to consider cost, nutritional and environmental aspects together in order to make sustainable decisions about the design of our future food system. The conflicting nature of these objectives, however, complicates this process.

Using traditional Operations Research techniques in combination with LCA data, this research presents a novel application in the context of a sustainable food system. The paper addresses a multi-objective network design problem for the food system under consideration of product and nutrient demands, broadening the scope of the considered network by taking into account interlinkages between different food supply chains. The proposed model incorporates sourcing, processing and transportation decisions, minimising both environmental (e.g. land use, climate change, fossil fuel depletion, etc.) as well as cost aspects while respecting the nutritional requirements of the society. Building on the work of other research, we aim to investigate the impact of a shift from meat-based to plant-based dietary consumption on the supply chain configuration. We illustrate the food system based on a nutritional case study and underpin it with real-life LCA data. In our analysis we investigate trade-offs between the conflicting objectives and highlight possible shifts from one environmental burden to another. Furthermore, we provide an overview over the allocation of these burdens in the network and the contribution of the different phases within the network's configuration.

The paper is organised as follows. In Section 2 a short literature background will be given. Section 3 will give a formal description of the problem. In Section 4 the multi-objective linear programming model will be introduced. Section 5 gives an overview of the experimental setup and the data input, before Section 6 presents the numerical analysis and findings from the model. Section 7 contains concluding remarks and some promising directions for future research.

2. Literature background

2.1. Sustainable supply chains

Over recent years, literature on supply chains and sustainability has received increasing attention within the scientific community, indicating an emerging trend within the field of green and sustainable supply chain management, design and planning. In this context, a number of review papers have been issued providing an overview over the current state-of-the-art. Table 1 provides a general overview of these review papers on sustainable supply chain management presenting the main insights for each study and the relevant findings in the context of this research.

The insights from the literature reviews show that most research fails to include the social component, focusing predominantly on environmental and economic aspects, which might be partly due to difficulties in the measurement and determination of the relevant social factors (Jaehn, 2016). Furthermore, there is a need for more holistic models, extending the system both in terms of the supply chain echelons considered as well as with respect to inter-organisational interactions and relations or global considerations. From a modelling perspective, multi-criteria decision making techniques and LCA approaches are the most widely applied methods and show further potential to support decision making in the field of SSCM. More industry specific and empirical research is needed in order to account for specific supply chain requirements. In this paper we will try to address some of these issues by considering a more holistic model within a global setting that extends the system, taking more echelons and interrelations into account. Focusing on the food industry, we make use of real life LCA data and investigate the application of multi-criteria decision making approaches to the problem at hand. In the following sections we will thus give a more detailed overview of these requirements in the context of agricultural and food supply chains and introduce the relevant literature and insights, followed by a brief overview of the use of multi-criteria decision making (MCDM) approaches in the field.

2.1.1. Sustainablity in agricultural and food supply chains

Focusing on applications in the area of production and distribution planning for agrifood supply chains, Ahumada and Villalobos (2009) present a review and categorisation of the relevant literature in the field. The study concludes that most approaches focus on the operational and tactical side of decision making within the supply chain framework rather than on strategic decisions and structural supply chain design issues. Presenting a critical taxonomy and hierarchical decision making framework for agrifood supply chains, Tsolakis, Keramydas, Toka, Aidonis, and Iakovou (2014) show that most of the existing research on agrifood supply chains is based on case studies focusing on specific parts of the chain rather than providing an integrated framework. Similarly, Higgins et al. (2010), focussing on Operations Research approaches for agriculture supply chains, highlight the increasing need to consider these complex systems/networks as a whole rather than solely optimising over parts of it. The work considers in particular the use of systems science methods, such as agent based modelling, dynamic systems and network theory to deal with this issue. Integrating sustainable supply chain management and dynamic capabilities within the same conceptual framework, Beske, Land, and Seuring (2014) conduct a review of sustainable supply chain management in the food context. Zhu et al. (2018) conduct a review of model-oriented applications of OR techniques in the field of sustainable food supply chains. Reviewing 83 papers, the research identifies the main food specific issues within the three sustainability dimensions and outlines a number of different future research directions, including the need to approach sustainable food supply chain design from a more global perspective. In this context of food supply chains, Dani (2015) provides a comprehensive overview over the scope of the chain decisions as well as current issues and challenges. The three main food-specific challenges for supply chain optimisation are identified as product quality, safety and sustainability (Akkerman, Farahani, & Grunow, 2010; Van der Vorst, Tromp, & Zee, 2009). Focusing on sustainability aspects, Iakovou, Bochtis, Vlachos, and Aidonis (2016) present a holistic framework for the design and operations of agrifood supply chains from an interdisciplinary perspective. The work highlights the industry specific needs and requirements with respect to policies, technologies, practices and solutions. Soysal, Bloemhof-Ruwaard, Meuwissen, and van der Vorst (2012) provide a literature review specifically focusing on quantitative modelling in the field of sustainable food logistics. Their findings show, that despite a growing interest in the area of food logistics, models incorporating food supply chain dynamics as well as sustainability aspects are still relatively scarce. The general trend in the scientific literature on food supply chains goes towards integrated and collaborative approaches while sustainability of the chain as a whole also

Table 1
Literature reviews on sustainable supply chain management (SSCM).

Author(s)	Year	Insights and Findings
Srivastava	2007	Review and classification of green supply chain management literature, providing an evolutionary timeline with focus on the environmental dimension.
Seuring and Müller	2008	Review and conceptualisation of a total of 191 papers in the area of SSCM, highlighting the relevance of government influences and other stakeholder groups. The review shows a clear under representation of the social dimension in the literature.
Mollenkopf, Stolze, Tate, and Ueltschy	2010	Review of the literature with emphasis on the relationships between green, lean and global supply chains, showing a need for more multi-functional approaches and strategic integration in a global context due to existing trade-offs between the different functional levels (such as for example purchasing and logistics), also calling for the development of more holistic systems approaches.
Carter and Easton	2011	Systematic review of the SSCM literature, using risk aspects and organisational structures to conceptualise sustainable operations
Ashby, Leat, and Hudson-Smith	2012	Systematic review of the current literature on supply chain management with social and environmental sustainability considerations. The work identifies a tendency towards theory and qualitative approaches, with most of the current literature focussing on "just the 'greening' of supply chain processes". The research denotes a clear need for more holistic approaches, that take supply chain relations into account, while the authors specify the potential benefits of LCA and closed loop approaches in this context.
Dekker, Bloemhof, and Mallidis	2012	Review of Operations Research contributions to the field of green logistics, thus addressing environmental aspects affecting design, planning and control decisions along the supply chain, including transportation, inventory and facility considerations. The study mentions the importance of metrics and multi-criteria decision making approaches in this context.
Hassini, Surti, and Searcy	2012	Literature review on SSC primarily elaborating on adequate metrics for sustainable operations, proposing two frameworks for the management and relevant performance measures in supply chains. The authors also note the need for more industry specific research due to different supply chain requirements.
Tang and Zhou	2012	Presentation of a profit-planet-people framework to understand the interrelations of activities impacting sustainability aspects, in combination with a categorisation of recent Operations Research literature with focus on quantitative models. The research shows that most literature fails to address the people dimension and lacks multi-location systems that take interactions in the supply chain into account.
Seuring	2013	Review of modelling approaches for SSCM, revealing that LCA is the most often applied modelling technique while most studies assess trade-offs between different sustainability issues with the social dimension not being enough accounted for.
Brandenburg, Govindan, Sarkis, and Seuring	2014	Review and categorisation of a total of 134 papers with focus on formal models in the area of SSCM, showing that multi-criteria decision making and LCA are the most commonly used tools for modelling. Based on the review, the research concludes that there is a lack of social aspects and inter-organisational perspective in the model-based literature.
Brandenburg and Rebs	2015	Review assessing and clustering 185 journal publications on quantitative modelling in the area of SSCM. The work identifies a lack of social aspects and denotes a need for more comprehensive models to describe the impact of entire sectors or industries.
Eskandarpour, Dejax, Miemczyk, and Péton	2015	Review of 87 papers in the area of SSC network design, focusing in particular on LCA based approaches. Findings show that the sustainability indicators are mostly still limited to greenhouse gas emissions, thus there is a need for the inclusion of broader life-cycle perspectives and social aspects.
Jaehn	2016	Conceptualisation of the field of sustainable operations addressing the interactions between the three sustainability dimensions. The paper is structured according to the fields within sustainable operations focusing on the use of operations research models and highlighting the main objectives for each dimension within the specific field.

receives more and more attention, as integrated approaches and collaboration between agents can yield greater benefits in terms of optimisation and raise standards (Higgins et al., 2010; Smith, 2008; Van der Vorst et al., 2009). However, more holistic approaches focusing on the strategic decision making level are still lacking.

2.1.2. Multi-criteria decision making approaches in sustainable supply chain design

As literature incorporates a greater variety of aspects into the decision making processes related to supply chain management, multi-criteria decision making (MCDM) methods, such as multi-objective optimisation, are becoming increasingly popular in the area of sustainable supply chain management. Banasik, Bloemhof-Ruwaard, Kanellopoulos, Claassen, and van der Vorst (2016) provide a conceptual framework and review of MCDM approaches in the field of green supply chain design and, given the new and emerging nature of the field, identify a need for more research in the area. Hayashi (2000) reviews multicriteria applications in the context of agricultural research management with the aim to evaluate and classify the criteria used. The study includes both multi-attribute and multi-objective methods. Linnemann, Hendrix, Apaiah, and van Boekel (2014) show the potential of MCDM for evaluating alternatives and increasing transparency in the context of food supply chain design by applying Multi Attribute Value Theory (MAVT) and Analytic Hierarchy Process (AHP) to the case of Novel Protein Foods. Mallidis, Dekker, and Vlachos (2012) propose a multi-objective model for supply chain design minimising cost as well as emissions and apply it to a supply chain network in South-Eastern Europe. Nagurney and Nagurney (2010) present a multi-criteria modelling framework for supply chain network optimisation with capacity considerations, optimising both cost as well as emissions of various chain activities. Oglethorpe (2010), presents the use of goal programming to address different economic, environmental and social goals in the context of alternative food supply chain strategies, applying the concept to local, regional and national decision making levels. Validi, Bhattacharya, and Byrne (2014) consider a two-layer food supply chain distribution system in the context of multiple objectives, optimising both costs and emissions of the distribution routes. Soysal, Bloemhof-Ruwaard, and Van der Vorst (2014) present a multi-objective model for perishable products with application to the beef network. The model minimises cost and emissions under consideration of load factors, road structures and fuel types. Minimising cost, emissions and delivery time, Bortolini, Faccio, Ferrari, Gamberi, and Pilati (2016) propose a multi-objective model for multi-produce, multi-level distribution network planning for perishable products. The research is applied to the case of a consortium distributing fresh products to European retailers. Allaoui, Guo, Choudhary, and Bloemhof (2018) develop a two stage hybrid multi-objective approach based on the AHP method and a multi-objective

optimisation model for the design of sustainable agri-food supply chains. The research includes social aspects in the objectives by considering the number of jobs created in addition to the water footprint, emissions and economic costs. In conclusion it can be said, that MCDM approaches are a prevalent and useful tool to deal with the different and often conflicting objectives and criteria in the field of sustainable supply chain design. However, the objectives addressed in the literature are mostly still limited to cost and greenhouse gas emissions.

2.2. Sustainable food consumption

With regards to food consumption a wide variety of contributions to the literature was made over recent years analysing the composition of diets according to a number of different criteria such as health, cost and sustainability. In this context, Macdiarmid et al. (2012), Ribal et al. (2016), Tyszler, Kramer, and Blonk (2015) and Wilson et al. (2013) present decision/diet models based on linear programming techniques, in order to determine the optimal composition of human diets under sustainability considerations, thus taking into account costs, greenhouse gas emissions and nutritional aspects. The findings of these studies show that switching to a more plant-based diet generally has the highest potential to reduce the environmental impact and can be achieved without a loss in the nutritional value. Hallström, Carlsson-Kanyama, and Börjesson (2015) show similar findings based on their review investigating 49 dietary scenarios with respect to their environmental impact in terms of land use and greenhouse gas emissions. Life cycle analysis (LCA) is often used to evaluate food choices based on their environmental impact and provides a number of different indicators for the sustainability assessment of foods (Mogensen et al., 2009). While these indicators are dependent on the life cycle of the product and therefore closely linked with the supply chain, Verkerk et al. (2009) show, based on an example, that links also exist between supply chain design in the food industry and impacts on nutritional intake and human health. Given these links, consumption and production choices should be considered in an integrated framework (Clark, 2007). In general, research on sustainable diets fails however to consider the impact of the underlying production system or interrelations between products, while the environmental aspects considered are mostly limited to greenhouse gas emissions.

3. Problem description

Given the gaps identified in the literature background, this study aims to present an integrated modelling approach, addressing the global food system, consisting of production, distribution and consumption activities, in a more holistic way by taking into account the different stages and inter-linkages in the underlying supply network. Individual food chains are composed of several steps, starting with agricultural production followed by transportation and further processing of produce, before the final distribution to retailers and customers occurs. Transportation can often be done with multiple transport modes, such as for example truck, freight ship or plane. The choice of available transport mode is thus considered a variable in the model, the transport distances are mode dependent and the availability of a mode is based on country specific infrastructure. In practice, there are often many sources of agricultural goods, several processing options and multiple destinations. In addition to this, due to links and interrelations between products, the whole network can get even more complex, including several processing steps, different processing options, side streams, backward loops and by-products, linking one single product to a variety of other products.

Fig. 1 provides a generic representation of the food network from agricultural production up to the nutritional contribution at consumer level, including different sourcing locations, processing and product choices. The problem gets increasingly complex depending on the number of agricultural crops, products and processing steps involved in the network. The overall objective of the model is to find the optimal network design in terms of sourcing locations, transport modes and processing options as well as the optimal mix and quantity of products produced, optimising a number of sustainability indicators.

3.1. Sustainability indicators

Within the food system, decisions are guided by multiple and often conflicting objectives such as economic and environmental considerations, as these aspects are important for actors in order to stay competitive. In this context, Table 2 provides an overview over the selected sustainability indicators and the criteria for selection.

Cost is selected as the most commonly used indicator for the economic dimension. For the environmental impact indicators, the focus in this research is on climate change, land use, water use and fossil fuel depletion. The selection of environmental indicators is based on the principles and the review of LCA studies presented in Van Mierlo, Rohmer, and Gerdessen (2017). The most important characteristics were thus the frequency of use, to facilitate comparability with other studies as well as the relevance for the food system. Furthermore, the threefold classification of Hauschild et al. (2013) considering the quality of the LCA modelling was taken into account, where category 1 represents best practice and is therefore most recommended. The environmental indicators further cover all the ecological systems categorised by Jaehn (2016). Note, that while the environmental and economic dimensions of sustainability, are included in the form of objectives in this research, the social dimension is incorporated in the form of constraints concerning the dietary/nutritional intake. Given the difficulties associated to the quantification and measurement of other social indicators, dietary health was chosen as one of the most relevant issues in the context of food.

3.2. Case study

Given the complexity and size of today's globalised food system, the problem is reduced to a specific nutritional case study focusing on a limited number of products to choose from in order to supply only a selected number of nutrients, instead of a complete diet. While in reality the system is much more complex and involves a much larger amount of products, in this research the emphasis will be on the beef and dairy chains and a number of alternative products that are suitable to replace beef and dairy products in terms of their nutritional aspects. The reason for this choice is that, while the beef and dairy industry is an important source of certain nutrients within the human diet, such as zinc, iron, protein, vitamin B12 and calcium, it also contributes significantly to the environmental impact of the food system (Hallström et al., 2015; Notarnicola et al., 2012). A reduction in the consumption of beef and dairy products could therefore lead to substantial improvements in terms of the environmental impact of the entire system.

The beef chain in itself, however, is a fairly complex and resource intensive network. In comparison with other products, beef and dairy chains require significant input from other systems in the form of for example feed during the livestock production phase, while also producing a number of secondary products such as manure and other by-products during the processing phase further downstream, which then again link (back) into other systems. Fig. 2 provides a simplified schematic of the beef and dairy chain from agricultural production to final consumption.

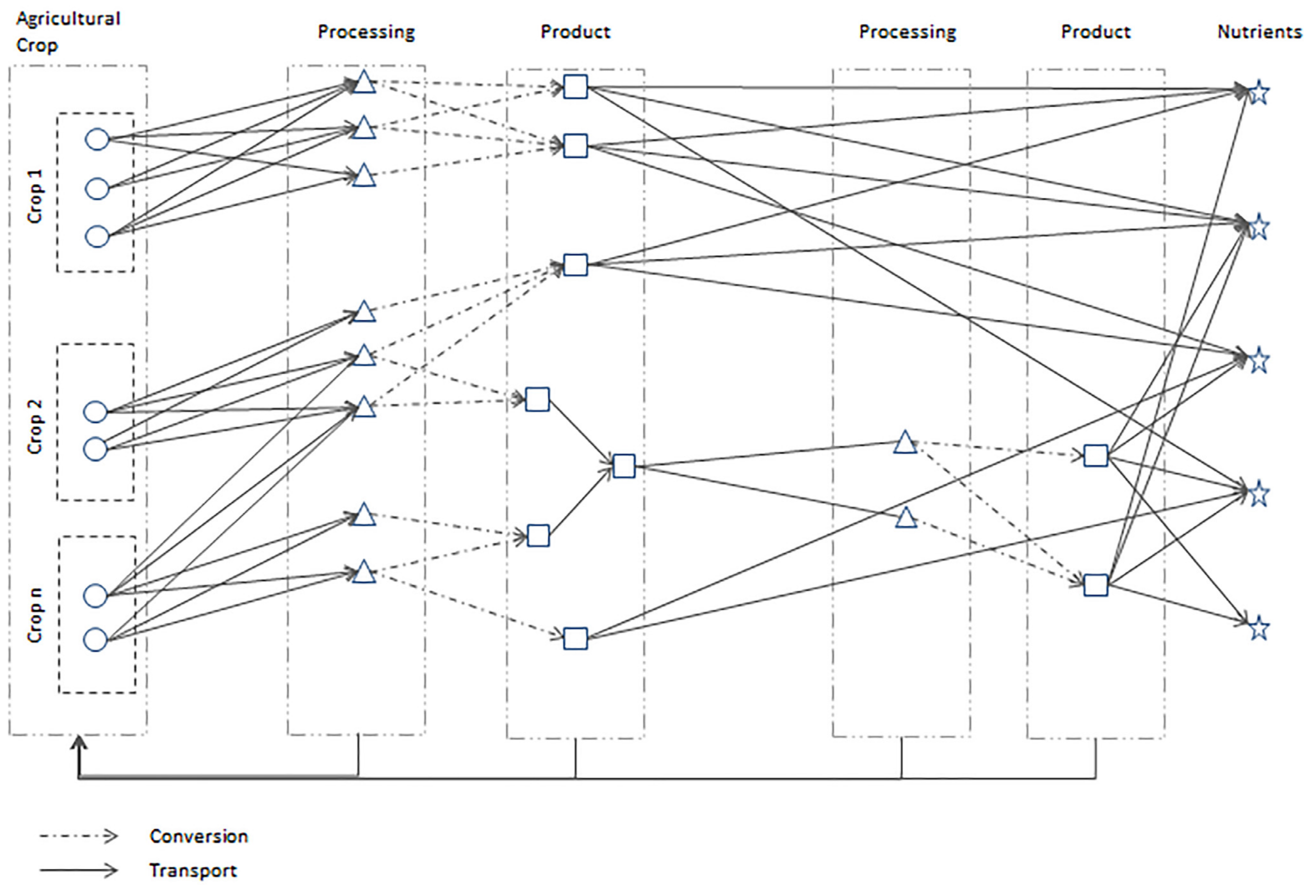

Fig. 1. Generic food network.

Table 2
Selected indicators and selection criteria.

Dimension	Indicator	Criteria
Economic:	Cost	Most widely used indicator for economic performance
Environmental:		
	Climate Change	Most commonly used environmental indicator impact on the global atmosphere related to food production classified in category 1 of Hauschild et al. (2013)
	Water Use	Impact on regional and global waterbodies related to food processing classified in category 2 of Hauschild et al. (2013)
	Land Use	Widely used impact on regional ecosystems closely related to food production
	Fossil Fuel Depletion	Impact on raw material sources in the primary sector related to food processing classified in category 2 of Hauschild et al. (2013)
Social:	Dietary Health	Most relevant for the food context

The substitute products are selected from suitable plant-based alternatives with regards to the important nutrients present in beef and dairy while also taking into account current Dutch consumption patterns. The key criteria for the selection of plant-based alternatives is thus their nutrient profile, as well as their popularity and acceptance in the Dutch population (Voedingscentrum, 2016). Given that vitamin B12 is not naturally present in plant-based products, we allow for supplementation of vitamin B12.

4. Mathematical programming formulation

This section provides a detailed description of the linear programming (LP) model and the notations and parameters used.

Sets and indices

A Set of locations (countries) indexed by i, j, l
C Set of consumer locations ($C \subset A$)
S Set of production locations ($S \subset A$)
P Set of products indexed by p, q, r
P_0 Set of processed products ($P_0 \subset P$)
m Index for transport mode
n Index for nutrient
f Index for environmental indicator
k Index for food category

Parameters

$cp_{i,p}$ cost of product p in location $i \in S$
$conv_{r,p}$ conversion factor from product r to product p
$rat_{p,q}$ ratio of by-product q when producing product p
$dist_{i,j}$ distance between i and j
ct_m cost of transport for mode m
$d_{i,n}$ nutrient demand at location $i \in C$ for nutrient n
$a_{p,n}$ nutrient content for nutrient n in product p
$ep_{i,p,f}$ environmental impact of product p at location $i \in S$ for sustainability indicator f
$et_{m,f}$ environmental impact of transport mode m for sustainability indicator f
$loc_{p,i}$ $= 1$ if production of product p is possible in location $i \in S$
$port_{k,i}$ portion size at location $i \in C$ related to food category k

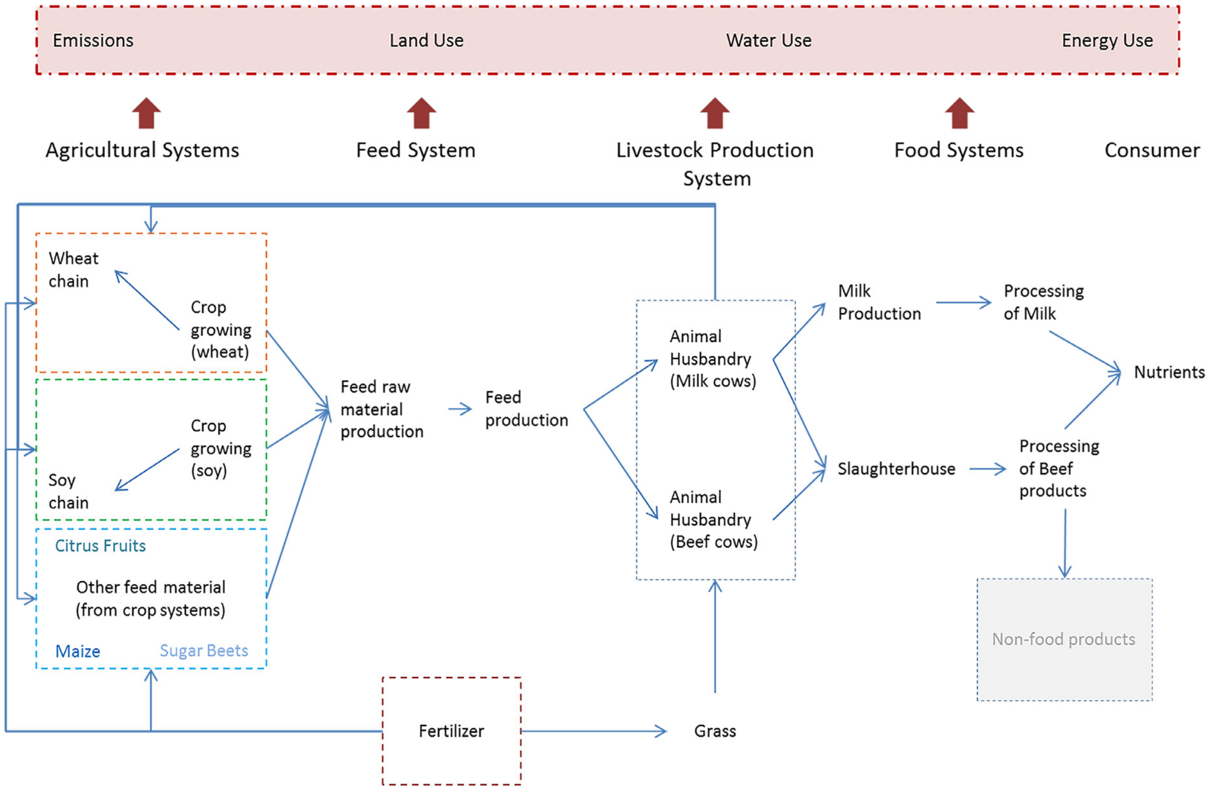

Fig. 2. Schematic of the beef & dairy network.

$D_{k,i}$ demand for food category k at location $i \in C$
α share of food category demand
$b_{p,k}$ $= 1$ if product p is in food category k
$rel_{r,p}$ $= 1$ if product r is a resource for product p

Decision variables
$x_{i,p}$ quantity of product p produced at production location $i \in S$
$z_{i,p}$ quantity of product p consumed at consumer location $i \in C$
$y_{i,j,p,m}$ quantity of product p transported from i to j with transport mode m in the final transport stage
$u_{i,j,p,m}$ quantity of product p transported between production locations i and j with transport mode m
$v_{p,i,r}$ quantity of product r needed at location $i \in S$ to produce product p
$w_{i,p}$ amount of product p wasted at location $i \in S$
$o_{i,n}$ amount of nutrient n consumed at location $i \in C$
EP_f total environmental impact related to production activities (including agricultural and processing) for indicator f
ET_f total environmental impact related to transportation for indicator f
TE_f total environmental impact for indicator f
TTC total transport cost
TPC total production cost
TC total cost

The total cost function for the network design problem is:

$$TC = TPC + TTC \tag{1}$$

The total environmental impact per indicator is given by:

$$TE_f = ET_f + EP_f \quad \forall\ f \in F \tag{2}$$

The above functions are used as objective functions in the model and minimised separately (for cost and different environmental indicators) or in the form of constraints in the ϵ-constraint method (Ehrgott, 2006).

The remaining costs are given in the following expressions:

$$TTC = \sum_{i \in S} \sum_{j \in C} \sum_{p \in P} \sum_{m \in M} dist_{i,j} ct_m y_{i,j,p,m} + \sum_{i \in S} \sum_{j \in S} \sum_{p \in P} \sum_{m \in M} dist_{i,j} ct_m u_{i,j,p,m} \tag{3}$$

$$TPC = \sum_{i \in S} \sum_{p \in P} cp_{i,p} x_{i,p} \tag{4}$$

The specific environmental impact functions are given by the following:

$$ET_f = \sum_{i \in S} \sum_{j \in C} \sum_{p \in P} \sum_{m \in M} dist_{i,j} et_{m,f} y_{i,j,p,m} + \sum_{i \in S} \sum_{j \in S} \sum_{p \in P} \sum_{m \in M} dist_{i,j} et_{m,f} u_{i,j,p,m} \quad \forall\ f \in F \tag{5}$$

$$EP_f = \sum_{i \in S} \sum_{p \in P} ep_{i,p,f} x_{i,p} \quad \forall\ f \in F \tag{6}$$

The demand is determined by α, which controls the share of food category/product demand in the model, given by,

$$\alpha\ D_{k,i} \le \sum_{p \in P} b_{p,k} z_{i,p} \quad \forall\ k \in K, i \in C \tag{7}$$

and the nutrient demand,

$$d_{i,n} \le \sum_{p \in P} a_{p,n} z_{i,p} \quad \forall\ n \in N, i \in C \tag{8}$$

with the consumption of product categories constrained by portion sizes:

$$port_{k,i} \geq \sum_{p \in P} b_{p,k} z_{i,p} \quad \forall\ k \in K, i \in C \tag{9}$$

The quantity of products consumed has to be transported to the consumer:

$$z_{j,p} \leq \sum_{i \in S} \sum_{m \in M} y_{i,j,p,m} \quad \forall\ p \in P, j \in C \tag{10}$$

The quantity of products transported to the consumer has to be less or equal to the quantity produced:

$$\sum_{j \in C} \sum_{m \in M} y_{i,j,p,m} \leq x_{i,p} \quad \forall\ p \in P, i \in S \tag{11}$$

The blending and resource constraints ensure that all the required resources needed for production of a product are available at the production location:

$$v_{p,i,r} = conv_{r,p} x_{i,p} \quad \forall\ p \in P_0, r \in P, i \in S \tag{12}$$

$$\sum_{p \in P} rel_{r,p} v_{p,j,r} = \sum_{m \in M} \sum_{i \in S} u_{i,j,r,m} \quad \forall\ r \in P, j \in S \tag{13}$$

Produced products have to be transported to the place where they are needed as resources or consumed and otherwise are classified as waste:

$$\sum_{m \in M} \sum_{j \in S} u_{i,j,p,m} + \sum_{m \in M} \sum_{l \in C} y_{i,l,p,m} + w_{i,p} = x_{i,p} \quad \forall\ p \in P, i \in S \tag{14}$$

The by-product constraints link the production of a product to its by-products:

$$x_{i,p} = rat_{q,p} x_{i,q} \quad \forall\ p \in P, q \in P, i \in S \tag{15}$$

Defining some of the variables as dynamic in order to reduce the size of the model, the final model includes over 156 thousand rows (constraints) and more than 830 thousand variables. However, given its linear and continuous nature the model can be solved quickly by any standard LP solver.

5. Illustrative case description and data input

5.1. Illustrative case

The applicability of the model is illustrated based on a real life case study related to current consumption patterns in the Netherlands. In connection to the dietary contribution of the beef and dairy system, 5 key nutrients are identified: protein, iron, zinc, calcium and vitamin B12. To allow for dietary replacement, the plant-based alternatives are selected based on their nutrient profile with respect to these 5 key nutrients. It should be mentioned that vitamin B12 is not present in plant-based products and thus needs to be supplemented in a solely plant-based dietary consumption (Broekema & Blonk, 2009). As a result, 10 food categories are selected, comprising 25 products suitable for human consumption. Together with the resources and feed materials needed to supply these products, this results in a network of 72 different products. Examples of such products are feed ingredients for the beef and dairy system or different grains and flour for the production of bread.

The case furthermore includes a total of 39 locations for the sourcing and production of products. These locations are product-dependent, and hence the amount and composition of feasible locations varies per product. Seven different modes of transport have been included in the model, namely air, inland waterways, rail, truck as well as three distance related sea shipping modes. The availability of a mode choice is dependent on the infrastructure and geographical position of a country, while distances between countries are location and mode dependent. Distances within a country are set to be the same for all available modes and all countries (10km). On a global scale, where products are sourced from all over the world, the transportation within a country is assumed to have a minor impact in comparison to the travel distances between countries. Moreover, we assume that agricultural production locations and the facilities for further processing are likely to be located in close proximity to one another, in order to avoid product decay, save time and delivery costs. While this might be a strong assumption, it has been shown in the scientific literature that within agricultural systems the impact associated with transportation plays only a minor role (Garnett, 2011; Weber & Matthews, 2008).

5.2. Data input

The nutritional data for the selected food products were retrieved from the NEVO database (RIVM, 2013). Environmental impact values are based on country specific life cycle inventory data, containing all the inputs and outputs for each specific production and processing step. We apply the ReCiPe impact assessment method (Goedkoop, Heijungs, De Schryver, Struijs, & van Zelm, 2013) to translate the emissions and resource extractions into the four environmental indicators selected in Section 3.1. The functional unit, referring to the quantification of the product to which the inputs and outputs relate, is expressed per kilogram of product. In the case of multiple products resulting from the same production step, an allocation method needs to be selected in order to divide the process inputs and outputs among the different products. The chosen allocation method in this study is economic allocation and thus based on the economic value of the products. Note, that no specific system boundaries for the scope of the LCA are applied as each step of the life cycle is included as a separate choice in the model by using life cycle inventory data, instead of using aggregated LCA impact values. All the life cycle inventory data as well as the (by-)product relations and conversion factors are extracted from the Agri-footprint database (Blonk Agri-footprint, 2015a and Blonk Agri-footprint, 2015b). The environmental impact data for the different transport modes are taken from the same database. The cost figures for the different products, transportation and processing steps were obtained as part of an extensive data collection from the literature and other sources. In this context, Appendix A provides a list of the consulted data sources. In case cost figures were not readily available, the data was calculated based on information from other sources such as labour and energy requirements and the country specific labour and energy costs.

5.3. Scenarios

Using the data described above, the model is tested for different scenarios that are then compared with respect to their results. Further specifications of the individual scenarios are detailed in the following.

- *Base case*: The demand for different food groups ($\alpha = 1$) is taken from current daily consumption data based on the Dutch dietary consumption survey (Van Rossum et al., 2016) and scaled to the population level. The model is optimised for cost which seems to be most aligned with current consumer choice, thus representing a kind of status quo. Dietary supplements in the form of vitamin B12 supplements are not considered in this case, as no demand for this food category is included. The base case presents a reference case for the other scenarios and will be the basis for comparison.
- *Status quo scenarios*: Given the same setting as in the base case the model is optimised also with respect to different

Table 3
Payoff tables for product and nutrient demand scenarios.

	Base case	**Status quo**				**Supplement scenarios**				
	TC	**CC (%)**	**LU (%)**	**WU (%)**	**FD(%)**	**TC* (%)**	**CC* (%)**	**LU* (%)**	**WU* (%)**	FD*
Total cost (€)	**8953636**	126	129	121	120	**25**	70	40	134	55%
Climate change (kg CO_2 eq)	100,358,786	**48**	50	50	99	9	**6**	8	13	39%
Land use (m2a)	54,135,964	78	**71**	75	88	28	45	**13**	97	35%
Water use (m3)	380,568	213	102	**31**	190	114	10	95	**5**	75%
Fossil depletion (kg oil eq)	2200,016	97	127	112	**86**	93	51	89	83	**27%**

environmental objectives: climate change, land use, water use and fossil fuel depletion.

- *Supplement scenarios*: In these scenarios the demand is no longer expressed in the form of food groups but in the form of a nutrient demand ($\alpha = 0$). Therefore, the food category demand D_{ki} of the base case is converted via data on nutrient content (a_{np}) to obtain the nutrient demand d_{in}. Vitamin B12 supplementation is possible to provide the required amount while palatability constraints in relation to portion sizes are added to ensure acceptability and feasibility of the dietary consumption. Provided that a plant-based diet requires a different dietary consumption, portion sizes are assumed to be higher than current standard portion sizes for plant-based food products. Given these specifications, the model is optimised for the different objectives: cost, climate change, land use, water use and fossil fuel depletion.

Furthermore, a multi-objective analysis is carried out using compromise programming (Zeleny, 1973) for the different demand scenarios and the epsilon-method (Ehrgott, 2006) for selected indicators in the case of nutrient demand.

6. Numerical analysis

6.1. Optimising for single objectives

Using Xpress-IVE version 7.2., the model is solved for the different scenarios with respect to the aforementioned economic and environmental objectives, minimising a single objective at a time. As a result, different optimal solutions for the food system are obtained in connection with the different scenarios and the findings are compared in the following. Note, that in the following, nutrient demand scenarios are indicated with an asterix (*) in tables and texts.

In this context, Table 3 presents the cost and environmental impact values associated to the Base Case, while the cost and environmental impact of the optimal solutions for all other scenarios are expressed in percentages of the Base Case values. The optimised objective for each scenario is shown underlined and in bold. Comparing the scenarios, with respect to their total cost and environmental impact, using the Base case as a reference, water use shows the biggest improvement potential with 31% of the Base Case value for the Status Quo and 5% for the Supplement Scenarios. Fossil fuel depletion in contrast shows the smallest potential of improvement with values at 86% and 27% of the Base Case for the Status Quo and Supplement Scenarios. The Supplement scenarios generally have a higher potential to lower environmental impact. Moreover, the percentages shown in Table 3 indicate a shifting of burdens between the individual environmental impact indicators. For the Status Quo scenarios, this means for instance, that water use increases to 190% when fossil fuel depletion is minimised. In the case of the minimisation of climate change, water use is even higher, increasing to 213% in comparison to the Base case.

Fig. 3 further illustrates these findings, while also showing the contribution of the three main phases, i.e. agriculture, processing and transportation, to the overall impact values. It can be seen that within the food system, the main contributor to cost and the different environmental impact categories is in most cases the agricultural production phase, followed by the processing phase, while transport plays a minor role for most scenarios. The impact of each phase within the system varies however, so that the processing phase gains in importance and plays a key role for the minimisation of cost and land use objectives in the Supplement scenarios. As transport mainly impacts climate change and fossil fuel depletion and has no or only little impact on land and water use, a higher contribution to fossil fuel depletion can be seen for scenarios in which land or water use are being optimised.

Fig. 4 presents the impact value contribution of the countries selected as production and processing locations specified for each scenario. Note, that all values are given in percentages of the total impact values obtained in the Base Case (as shown in Table 3), values related to transportation are not assigned to a specific country and thus not included in this analysis.

Comparing the results for the different scenarios, the selected countries and their contribution to a specific impact indicator differ. For climate change for example, Indonesia is the biggest contributor in the Base Case, the FD and FD* scenario, while Malaysia is the main contributor to climate change in the Status Quo scenarios that optimise climate change (CC), land use (LU) and water use (WU). Comparing between impact indicators, it can be seen that the contribution of a country within a scenario varies per indicator. An example of this is France in the CC scenario, contributing a large share to water use but only little to all the other impact indicators. Another example is the LU* scenario, where the Netherlands accounts for most of the impact associated to the different indicators with the exception of land use, for which Belgium makes the most prominent contribution. This means that depending on the scenario a country might be more or less affected by the different environmental pressures, which can be denoted as a shift of burdens between countries. In addition to this, the figure shows that for many scenarios, most of the impact associated to a specific indicator can be attributed to only one or two countries, while the rest of the countries make just minor contributions, thus resulting in an uneven distribution of the pressures among the different countries. More generally, comparing the results with respect to product and nutrient demand, Fig. 4 again highlights the bigger improvement potential in the supplement scenarios (with nutrient demand), while also depicting a general trend for these scenarios towards smaller systems, consisting of fewer countries for production and processing locations.

This is linked to the number of product types within the system associated to the different scenarios. In this context, Table 4 presents the total number of product types for each scenario, distinguishing between consumed products, resources and unused side-streams within the system. From this it can be seen, that the total number of product types is considerably higher for scenarios including beef and/or dairy products (all product demand scenarios and FD* (see Table 5)) than for scenarios with plant-based consumption, requiring significantly less resources. In comparison

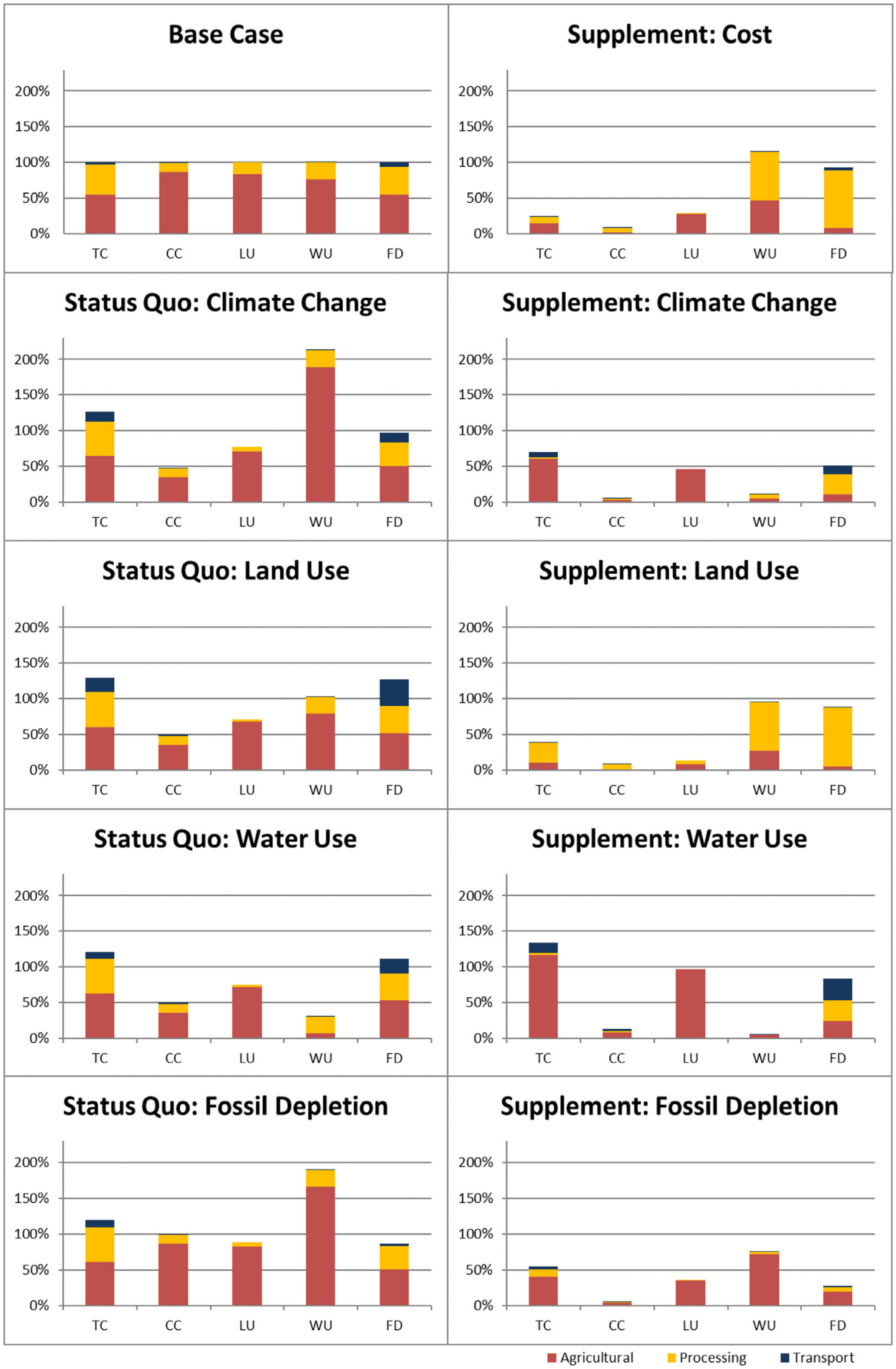

Fig. 3. Impact per Scenario for total cost (TC), climate change (CC), land use (LU), water use (WU) and fossil fuel depletion (FD), optimising over the different objective functions (in percentage of the base case).

to the number of products consumed, the number of resources is about 5 times the number of product types for the Base Case and Status Quo scenarios and for minimisation of fossil fuel depletion in the Supplement scenarios. Furthermore, due to the relationships and conversion between product types, there are scenarios in which not all product types are fully used or side streams of products are wasted.

Moreover, for the Status Quo scenarios, only two product compositions are observed, one for the scenarios CC and FD and one for the scenarios LU and WU, while for the supplement scenarios

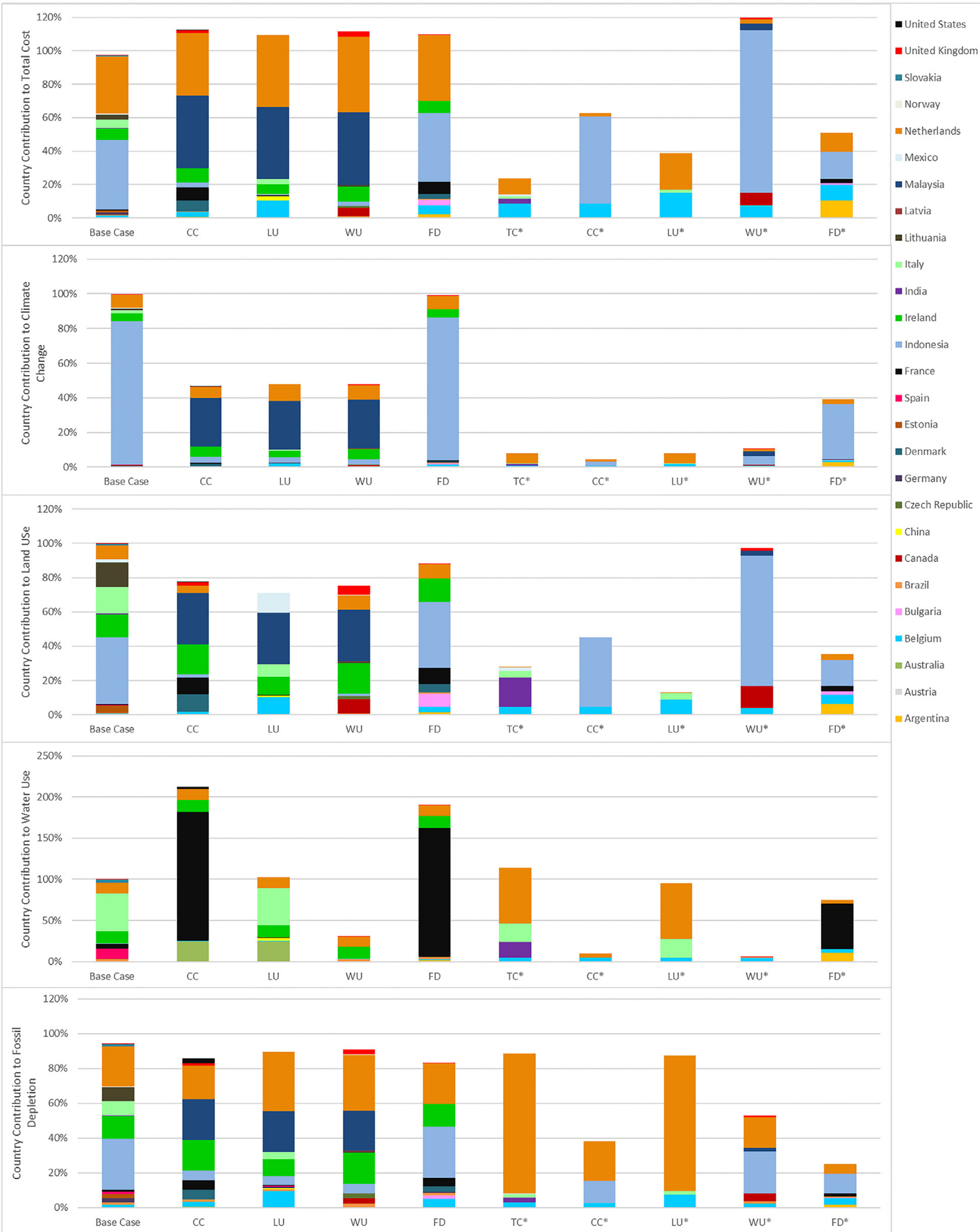

Fig. 4. Impact contribution per country specified for each scenario.

product composition experiences more flexibility. Investigating the product mix for consumption in greater detail, Table 5 emphasises the limited choice of product mixes for the scenarios with product demand. The table further highlights that the three product mixes observed in the case of product demand, only show minor differences in their composition, such as for example a switch from rye bread to wholemeal bread (CC/FD to LU/WU). Given the differences in the impact values for the different scenarios (outlined in Table 3), these findings indicate the importance of the underlying production system configuration and its impact on the sustainability indicators for the product demand scenarios. The supplement scenarios in contrast allow for more flexibility due to the nutrient

Table 4
Total Products within the System categorised by usage.

	Base case	Status Quo		Supplement scenarios				
	Cost	CC/FD	LU/WU	TC*	CC*	LU*	WU*	FD*
Consumed	9	10	10	5	3	5	4	5
Resources:	49	50	49	5	3	6	14	31
-Processed (no waste)	43	44	43	5	3	6	14	28
-Processed (partly wasted)	6	6	6					3
Unused side-stream							4	5
Total Produced	**58**	**60**	**59**	**10**	**6**	**11**	**22**	**41**

Table 5
Productmix consumed.

	Base case	Status Quo		Supplement scenarios				
Product (in kg)	TC	CC/FD	LU/WU	TC*	CC*	LU*	WU*	FD*
Milk, raw	5,964,000							
Cream, full		148,506	148,506					
Cream, skimmed								170,538
Milk, full		5,815,494	5,815,494					
Milk, skimmed								2,134,031
Beef (from dairy system)	52,526	52,317	52,317					
Veal	6988	6960	6960					
Beef (from meat cattle)	175,686	175,923	175,923					
Soybean drink				10,080,000		10,080,000		
Spinach, fresh	352,800	352800	352,800				4,386,134	5,040,000
Frozen Spinach (in Plastic)				5,040,000	5,040,000	5,040,000		
Beans, dry canned		67,200	67,200					
Chickpeas,canned	67,200			2,249,081				
Peanuts, without shell	84,000	84,000	84,000	152,028	4,039,001		5,040,000	7,26,808
Peanut butter	67,200	67,200	67,200				2,520,000	
Rye Bread	2,200,800	2,200,800						
White Bread						2,710,387		
Wholemeal bread			2,200,800			783,024		
Vitamin B12 Supplements				5.67	5.67	5.67	5.67	3.8

demand and therefore showcase a wider variety of product mixes, that clearly differ from the product demand scenarios.

6.2. Heterogeneous demand

While the potential impact reduction is significantly bigger for the supplement scenarios, the shift from the current consumption mix in the product demand scenarios to the consumption mixes in the supplement scenarios might not be easily accepted in practice, finding resistance in the population. Thus, it is interesting to investigate the economic and environmental impact in the presence of heterogeneous demand scenarios allowing for a more gradual change, instead of considering consumer behaviour to be homogeneous, where either food groups or nutrients are demanded. Heterogeneity is modelled by varying the share of α in constraints (7) from 0 to 1, with 0 representing the nutrient demand scenarios and 1 the food category demand scenarios. Fig. 5 presents the objective value change related to a change in α (x-axis) for each of the objectives. Note, that all values are denoted in percentages of the impact values obtained in the Base Case. The results presented in the figure show a smooth and continuous change in the assessed criteria, where the impact for each objective increases gradually with α. These results again emphasise that the improvement potential is biggest for the scenarios with homogeneous nutrient demand, while also showing that even minor changes in the demand can help to decrease the impact associated with the human diet.

6.3. Bi-objective optimisation: ϵ- constraint method

Given the conflicting nature of the different objectives and the trade-offs between them, a bi-objective analysis is carried out deriving sets of Pareto optimal solutions using the ϵ-constraint method. A detailed description of the method as well as other approaches for multi-criteria opti-misation can be found in Ehrgott (2006).

Two bi-objective analyses are carried out for the case of nutrient demand to determine the relationships between cost and climate change as well as water use and climate change. The analyses therefore investigate one relation between an economic objective (i.e. cost) and an environmental objective (i.e. climate change) and one relation between different environmental objectives (i.e. climate change and water use). Climate change was chosen for investigation as it is the most widely used environmental objective in the scientific literature, whereas water use represents a predominantly local impact indicator in contrast to the global impact of climate change. However, other interesting relationships might exist for other indicators, such as a potential conflict between land use and cost or land use and water use. The efficient solutions for both bi-objective analyses are calculated by minimising one of the objectives while the other objective constrains the problem, the process is iterated for the different ranges obtained from a sensitivity analysis with respect to the right-hand side of the constraint. Thus the number of iterations depends on the analysed scenario. The obtained sets of efficient solutions for the cases presented here are depicted in Fig. 6.

For the analysis based on cost and climate change, 15 iterations were needed to obtain the set of Pareto optimal solutions. The graph features a distinctive kink in the middle of the trade-off curve, dividing the curve into two line sections. The solutions to the left of the kink cohesively contain a smaller number of product types than the solutions to the right of the kink as the number of product types consumed generally decreases for more environmental friendly solutions. The different slopes of the two line

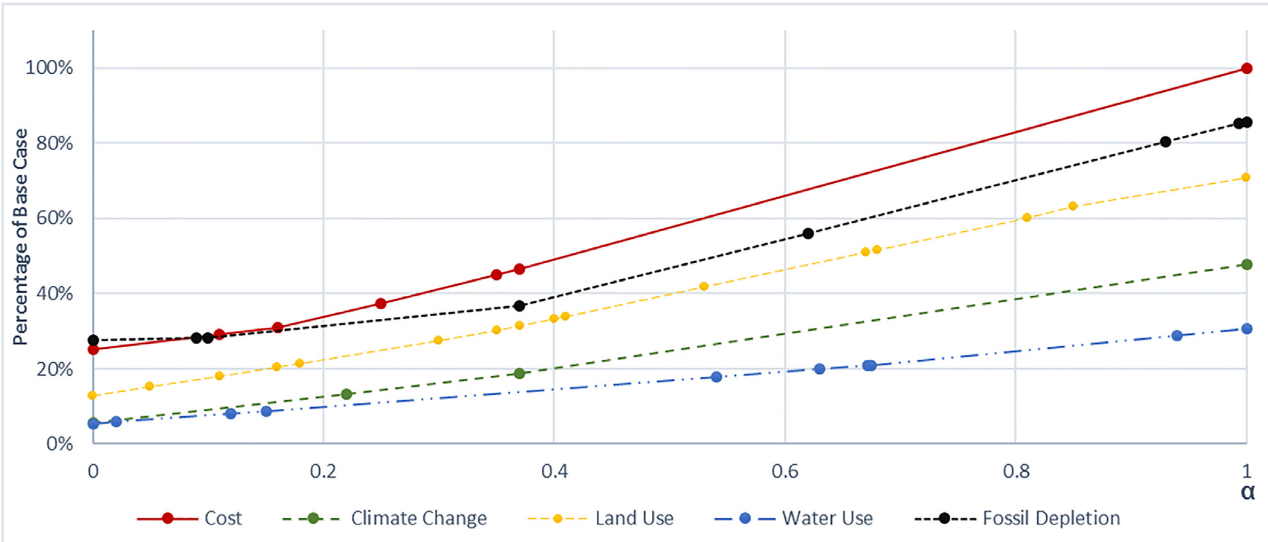

Fig. 5. Objective values as a function of the share of food category demand (α) in percentage of the Base Case.

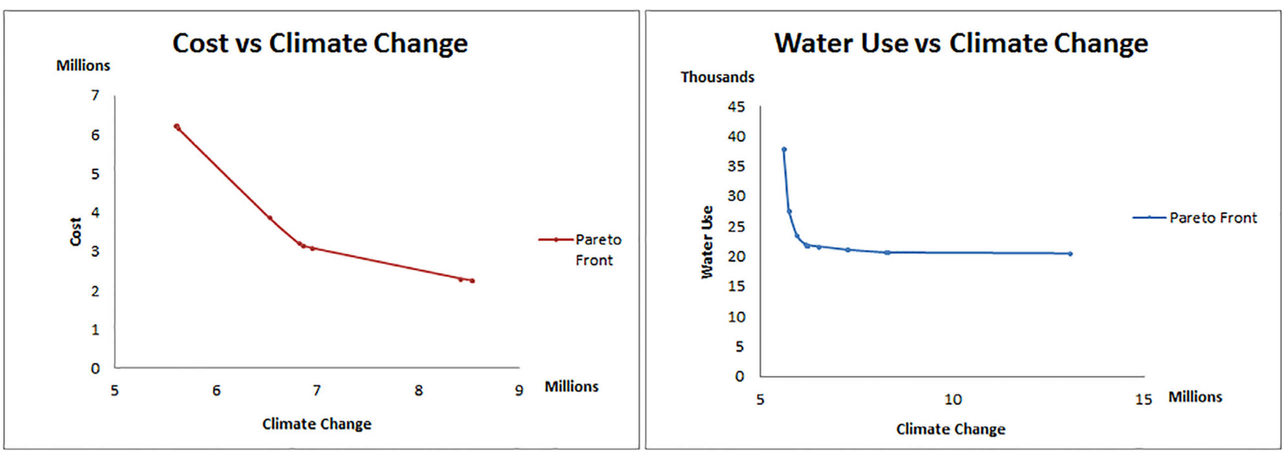

Fig. 6. Trade-off curves for multi-objective optimisation in the context of the supplement scenarios.

sections indicate that climate change reductions along the first section are more costly, whereas reductions in the second section require a smaller increase in cost. The changes in the solutions along a particular line section are mainly caused by changes in production location. The best solution depends on the decision maker's preferences, with the two end points representing more extreme preferences while the kink in the middle depicts a more balanced solution.

For the analysis based on water use and climate change, a total of 19 iterations were conducted to derive the set of Pareto efficient solutions. The trade-off curve in this case adopts a smoother curve, starting with a steep decline and merging into an almost flat continuation. In the flat part of the curve big improvements can be made with respect to climate change for a small increase in water use. This is mainly caused by changes in the composition of the product mix. Seven of the efficient solutions on this line segment include dairy products in the product mix, however the quantity of dairy products decreases for solutions with lower climate change impact. In the steep part of the curve, large improvements in water use can be obtained by relatively small increases in climate change. Shifts are caused by both, small changes in product mix composition as well as the choice of production locations.

6.4. Multi-objective optimisation: compromise programming

While the bi-objective approach using the ϵ-constraint method provides interesting insights regarding the trade-offs between two different objectives, it does not take all the objectives into account. Given that all objectives are considered of equal importance, it is interesting to consider the relationships between all the objectives using a multi-objective approach. Compromise programming (CP), first developed by Zeleny (1973), is a useful tool in this context, allowing the decision maker to find compromise solutions, that are as close as possible to the desired solutions for each of the conflicting objectives. The basic idea of CP is thus to first establish the "ideal point" for each of the objectives j, i.e. the optimal value associated with each single objective, and then to minimise the distance between these ideal points and the compromise solution. Given that the units are often different between indicators, distances are normalised using the distance between the ideal point and a pessimistic point as a reference. The degree of closeness d_j is then defined by

$$d_j = \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} \tag{16}$$

where Z_j^* refers to the ideal point, $Z_j(x)$ refers to the point under consideration and Z_{*j} is the pessimistic point. Note, due to the complexity of identifying the actual worst point associated with an indicator, the pessimistic point is estimated by the worst solution found for an indicator when optimising for single objectives. The distances between solutions and the ideal point is measured using the following set of distance functions:

$$L_p = \left[\sum_{j=1} (d_j)^p \right]^{1/p} \tag{17}$$

The L_1 and L_∞ metric, providing the bounds of the compromise set (Yu, 1973), can be obtained using the following formulations:

$$\text{Min} \quad L_1 = \sum_{j=1} \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} \qquad \text{s.t.} \quad x \in X \tag{18}$$

and

$$\text{Min} \quad L_\infty = D_{max} \qquad \text{s.t.} \quad \frac{Z_j^* - Z_j(x)}{Z_j^* - Z_{*j}} \le D_{max} \quad \forall j \in J \quad x \in X \tag{19}$$

The extended goal programming model of Romero (2001) given by the following formulation

$$L_e = (1 - \lambda) D_{max} + \lambda \sum_{j=1} d_j \tag{20}$$

is applied to find solutions, taking into account both efficiency (L_1 metric) and equity (L_∞ metric) considerations, with λ being a control parameter, regulating the bias towards efficiency of the solution. The analysis is carried out in the context of both product and nutrient demand.

Results of the analysis are shown in Fig. 7, comparing the compromise solutions (represented in green) to the solutions found for the single objective optimisation (represented in blue). The depicted compromise solutions are L_1 ($\lambda = 1$), L_∞ ($\lambda = 0$) and an intermediate solution L_e with $\lambda = 0.3$. The figure shows, that CP provides intermediate values in the lower ranges of each indicator, resulting in overall more balanced solutions. Moreover, the different compromise solutions show similar results for the individual impact indicators with the exception of water use, where the difference between the L_1 and L_∞ solution is more prominent.

7. Discussion and conclusion

This paper proposes an integrated modelling approach for the global food system under nutritional considerations, optimising over both cost and environmental objectives. To the best of our knowledge this research presents the first (multi-objective) network design model for a holistic food system in which consumption and production decisions are incorporated in a common framework.

Furthermore, the applicability of the model is illustrated based on a real life case study and tested for different scenarios. The scenarios investigated in this research can be grouped in product demand scenarios and scenarios with a nutrient demand. Within a group the scenarios differ with respect to their objective function, optimising cost and various environmental indicators, namely climate change, land use, water use and fossil fuel depletion. Product demand scenarios, consisting of the Base Case and Status Quo scenarios, depict the current consumption patterns in the Dutch society, whereas the scenarios with a nutrient demand (Supplement Scenarios) describe possible future what-if scenarios. Given the size of the system under consideration, as well as its holistic nature and the various aspects included in the model and numerical analysis, the findings of this research are manifold.

While the paper investigates supply chain activities, with respect to three different phases in the food system, i.e. agricultural production, processing and transportation, the findings show that agricultural production is the main contributor in the system. This is in line with other scientific research (Garnett, 2011; Weber & Matthews, 2008) and has the effect that the focus in this discussion will be predominantly on findings related to production aspects.

Viewing the food system as a whole, the findings show, that consumption patterns impact the size and configuration of the underlying system. Plant-based consumption generally requires less resource input from other supply chains and hence results in simplified systems with less intermediary steps and greater transparency. Animal systems on the other hand require extensive resource input in the form of feed and often comprise of several processing steps, adding to the complexity of the system. Considering the different phases in the system, the impact per phase varies depending on the objective function and for the different environmental impact indicators. This can be attributed to the fact that the different phases in the system have different environmental profiles, contributing differently to the individual indicators. In most cases however, the agricultural production phase is predominant, contributing most to cost and environmental impact, followed by the processing phase, whereas the impact of transportation is of minor importance in these kind of systems. Measures aimed at improving cost and the environmental impact of the system, such as the development of technological advancements or new production methods, should be targeted accordingly to maximise their potential.

The findings with respect to the product mix, show a higher product diversification in the scenarios with product demand, whereas the nutrient demand offers more flexibility and thus results in fewer product types consumed with greater variation between scenarios. The observed optimal product mixes for the different scenarios and their contribution to different environmental impact indicators, confirm the findings of other researchers, that a shift towards a more plant-based dietary consumption holds the greatest potential to reduce the environmental burden (Hallström et al., 2015). For most objective functions in the Supplement scenarios, with the exception of the minimisation of fossil fuel depletion, the results even suggest a shift to a fully plant-based dietary consumption. This is, however, only possible due to the vitamin B12 supplementation. In this context, it should also be noted, that while it holds the greatest potential to reduce the environmental burden, a fully plant-based dietary consumption, requires significant changes in the composition of the diet. Thus, it might be less accepted by the population, even though it is feasible to supply the nutrient demand with the plant-products and supplements included in this research. The analysis considering heterogeneous demand scenarios shows in this context however, that even small changes in our dietary consumption can help to decrease the environmental impact associated with our diet. For future research, the inclusion of other product types, such as meat substitutes, in combination with more advanced palatability constraints could make the results more widely acceptable and realistic. In addition to this, it could be of interest to investigate government and other stakeholder measures that can influence demand shifts in combination with social aspects.

The findings further depict a shifting of burdens between the individual indicators due to existing trade-offs. This means, that the minimisation of one indicator can lead to a substantial increase of another indicator and thus can have a tremendous effect on a different aspect of the environment.

The bi-objective approach, using the ϵ-constraint method, provides a way to investigate these trade-offs and obtain a set of efficient solutions, while the multi-objective approach using compromise programming provides more balanced solutions dealing with multiple conflicting objectives, by considerably improving the

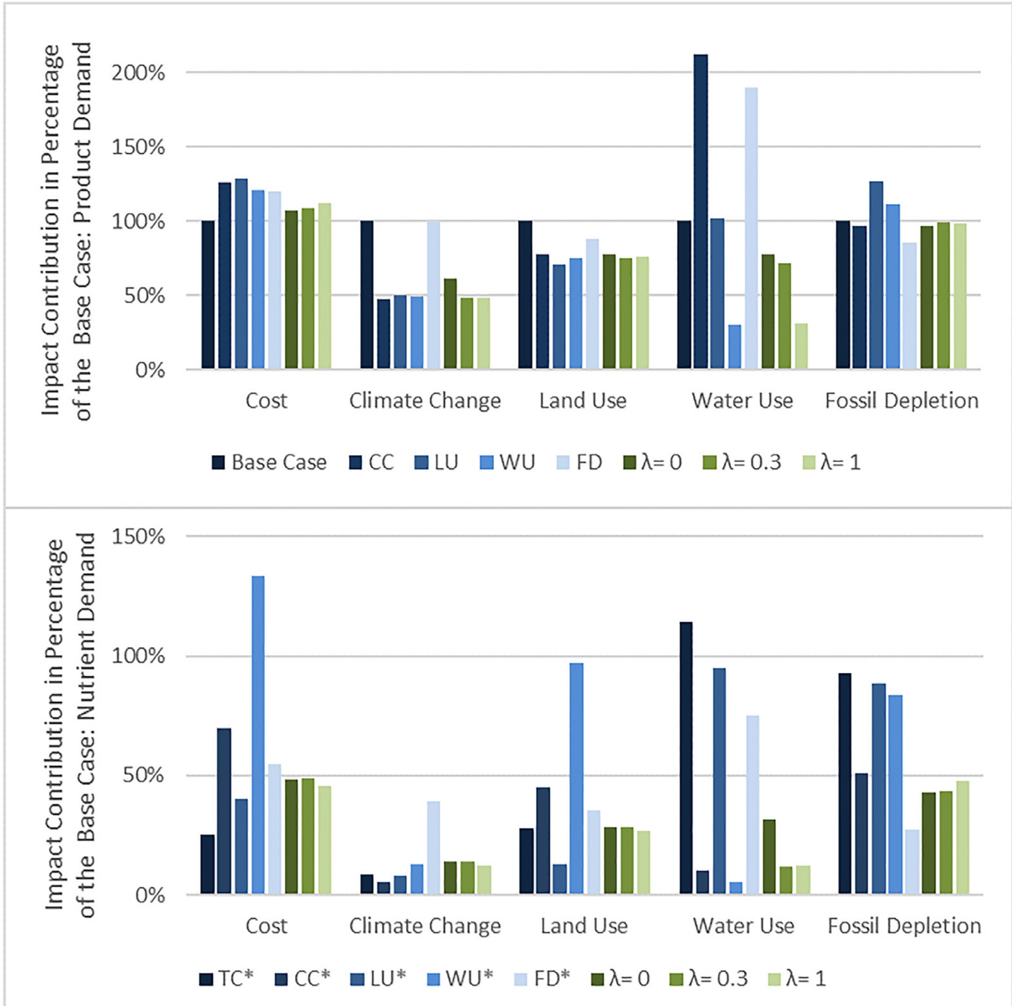

Fig. 7. Impact Comparison between Scenario and Compromise Solutions for both Product and Nutrient Demand in Percentage of the Base Case.

environmental factors while only moderately increasing costs. Based on these findings, the decision maker can choose the best solution based on his or her preferences.

Moreover, a shifting of burdens can also be observed between countries (i.e. the production locations), as the contribution of a country differs depending on the scenario, as well as for cost and the individual environmental indicators. Thus, the global optimal solution might result in an increase in the burden from the local perspective of certain countries. This raises two issues. Firstly, in the context of predominantly local impact factors, such as water or land use, an increase in a country where water or available land is scarce, can be more severe and harmful for the environment than in other countries. This should be taken into account in the decision making progress and investigated further in future research by for example including capacities. Secondly, for global impact factors, such as climate change, it is important to raise awareness of the global nature of the problem and encourage international collaboration as a shift between countries can lead to an overall reduction. This outsourcing of emissions on the other hand questions the validity of current emission schemes and requires policies that penalise and compensate in a fair manner.

While there are valuable insights to gain from this study, it is important to note that it has its limitations and that some of the underlying assumptions require further attention. One of the main limitations in this study are the system boundaries and the amount of products, processing options and production locations considered, as in reality the amount of options in the food system is significantly bigger, whereas this study relies on a limited number of products. It should be noted in this context, that the results and optimal solutions obtained are product dependent and thus are likely to change with different product input. Furthermore, in practice, the relation between different products, such as resource requirements and by-product ratios, are not inevitably fixed but depend on prices and other factors in the system, such as for example availability and quality aspects. This holds especially true for the composition of feed and should be investigated further in future research.

Another important limitation in the context of the food system is that in reality there are more actors and demand locations in the system, than considered here. Every country has a demand and supply for food products and given the limited resources there is competition between countries. Countries have production capacities and an interest to maintain some level of self-sufficiency and not become too dependent on the supply of other countries. Seasonality plays an important role in relation to the production of food products within a country and the availability of food products is subject to uncertainty due to weather conditions and other external influences.

In addition to this, the number of nutrients included in the model only represents a small part of the human diet and nutritional requirements. A shift from animal products towards a more plant-based dietary consumption is likely to affect the nutritional

intake in multiple ways and not just limited to the nutrients considered here. For future research, it could thus be of interest to examine the effects of this shift in a broader dietary setting, taking into account a more complete nutritional profile.

While social sustainability is here represented in the form of health considerations, i.e. the nutritional intake, there are many other aspects that are of relevance from a social perspective, such as fair trade, animal welfare and employment aspects. Most of these aspects are however difficult to aggregate, quantify and measure in a global context where numerous different social systems converge and interact.

This model and its findings rely on a substantial amount of data and while an extensive amount of data was gathered from LCA studies and a variety of literature sources a number of assumptions had to be made that might impact the results of the model. The data quality might therefore vary for different countries, processing and product types. Moreover, whereas this study assumes all data to be deterministic, this is hardly viable in practice due to uncertainties. The model could thus be extended using stochastic or robust approaches in order to account for such uncertainties in the data.

Acknowledgements

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Appendix A. Data sources cost data

https://ec.europa.eu/agriculture/sites/agriculture/files/markets-and-prices/price-monitoring/market-prices-vegetal-products_en.pdf

http://www.fao.org/faostat/en/#data/PP

http://www.fao.org/faostat/en/#data/PM

http://future.aae.wisc.edu/data/weekly_values/by_area/3229?tab=feed

http://edepot.wur.nl/246392

http://ec.europa.eu/agriculture/rica/pdf/beef_report_2012.pdf

https://ec.europa.eu/food/sites/food/files/animals/docs/aw_arch_report_parti_en.pdf

http://www.irishexaminer.com/farming/news/silage-costs-you-at-least-28-32t-320467.html

http://www.fao.org/docrep/012/al376e/al376e.pdf

http://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs

http://www.ifcndairy.org/media/pdf/publications2014/Benchmarking-Cost-of-Milk-Production-in-46-Countries.pdf

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https://www.bls.gov/fls/ichcc.pdf

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